

# Acquisition, Processing and Evaluation of Down Hole Data for Monitoring Efficiency of Drilling Processes

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## Abstract

This paper presents a study carried out in collaboration with a company leader in the production of drilling tools and sensors. Data were gathered during a period of four months in two horizontal well of an oil field with the aim of assessing the relationship between Mechanical Specific Energy (MSE) and drilling efficiency through the analysis of the most significant drilling parameters.

There are several models and measurement systems available for measuring such parameters, however in many practical cases the possible maximum performances are not achieved and this suggests the idea that there is still room, from a research point of view, to increase acquisition accuracy and their correct evaluation. In this study, down hole data were acquired to calculate significant parameters for assessing drilling performances which can contribute to the avoidance of errors in torque calculation due to the effect of drill string friction and the consequent distortion of MSE curve.

Moreover, the same data implemented in a model for Rate of Penetration (ROP) calculation and a map correlating RPM and Weight on Bit (WOB) values with Rate of Penetration was drawn.

## Keywords

*Mechanical Specific Energy; Drilling Rate; Weight on Bit; Drilloff Curve*

## Introduction

Oil well drilling, a complex and difficult control process, is characterized with low efficiency.

Nowadays the oil well costs are very high and the optimization of the process, in terms of increasing performances and reducing time, is a key factor for success. Systems for monitoring in real time parameters affecting drilling processes have been gaining increasing importance. Today's sophisticated

data acquisition systems for both surface and downhole drilling data have greatly enhanced the understanding of the basic drilling mechanics and helped in the identification of major dysfunctions particularly harmful downhole vibrations. Various methods are now being used to optimize drilling practices by monitoring efficiency indicators such as mechanical specific energy and preventing harmful vibrations by adjusting drilling parameters in real time (Pessier and Fear M.J., 1992). In this study data acquired on field have been analyzed to evaluate and identify issues of drilling processes. Diagnostic tool has been used whose concept and relative formula were introduced in 1964 (Teale, 1965). MSE is defined as the amount of energy required per unit volume of rock drilled and represents the energy necessary to drill a fixed volume of rock (Kpsi).

The monitoring of MSE can provide information for recognizing dull or damaged bits; select an appropriate bit and WOB and RPM for a bit and rock type, respectively; and avoid the poor mud circulation.

Another important parameter that influences the drilling performances is the geology of the formation. In order to identify its main characteristics such as the resistance and abrasiveness of the rock and the best drilling strategy, there are different available techniques.

The most widespread measurements performed are:

- gamma ray emitted by the soil that is able to estimate the presence of clay;
- compressive acoustic transit time that provides information on the rock porosity and consequently on the type of constituent material;
- mechanical resistance of the rock.

This last parameter can be evaluated in two ways: measuring the Unconfined Compressive Strength (UCS) and the Confined Compressive Strength (CCS). UCS represents the force, applied to a defined area  $A$ , necessary to deform the rock at atmospheric pressure; whose value is characteristic and fixed for each type of formation and represents the minimum value of the relative mechanical resistance. CCS is the force on a defined area  $A$ , needed for the deformation of a volume of rock around which is applied to a pressure  $P$ . CCS measures the maximum value of the resistance for each rock. The Real value of the Compressive Strength (RCS) of a defined formation will be an average value within UCS and CCS

The overall efficiency of the drilling process can be evaluated as:  $\mu = \text{RCS} / \text{MSE}$ .

Its maximum value corresponds to the minimum energy introduced in the system, e.g to the value of UCS.

The monitoring of MSE represents a key element of the Fast Drill Process (FDP); a process that aims at drilling with the highest possible ROP (technically and economically). ROP is the measured distance that the drill bit or other drilling tool penetrates the subsurface formations in a unit length of time. All optimization schemes focus on identifying the best of these parameters relative to other settings.

MSE should be kept as low as possible and ROP as high as possible in order to increase the efficiency of the process; which can be obtained by varying WOB, rotary speed, and mud flow within normal operating limits. Other than identifying performances limiting factors, MSE can be used as a quantitative measure for assessing costs-benefits associated with redesign of drilling process.

Usually drilling engineers want to maintain MSE value as close as possible to a formation's true compressive strength. Unexpected changes in MSE may indicate changes either in rock properties, or drilling inefficiency, or both.

It has been demonstrated that MSE can be used to identify the three most common causes of inefficiencies: bit balling (due to the accumulation of drilled material on the cutting tool that causes the energy transferred to the rock formation to decrease), bottom hole balling (caused by the accumulation of material at the bottom hole that reduces the energy transfer from the bit to the rock below it), and vibrations.

In this study the acquisition of the field data has been performed in collaboration with a company leader in the production of drilling tools and sensors that, for privacy reasons, is not named. This paper is organized in the following manner: a brief scientific background; a description of the material and methods used; the results obtained and the tests performed, with some examples explaining their diagnostic value; discussions of the results and conclusions.

### *Scientific Background*

There are several authors that have studied and developed tools and relationships for optimizing drilling performances as well as have investigated the correlation between Mechanical Specific Energy with drilling efficiency. One of the most common test for the optimization of the drilling performance is the "drill rate" test, in which various WOB and RPM settings are experimented. Weight on bit is the total amount of downward force placed on a bit by the entire weight of the drill stem. The drillers then use the combination of WOB, RPM and torque settings which provide the best rate of penetration.

The curve represented in figure 1, known as drilloff curve (Dupriest and Koederitz, 2005), identifies three main regions of bit efficiency: in regions I and III the bit operates in conditions of inefficiency where a disproportionate amount of energy has to be used for a given ROP; in region II, instead, the bit works at its maximum efficiency giving that an increase of WOB produces a linear increase of ROP and a consequent constant value for MSE. The point in which the rate of penetration stops responding linearly with increasing weight on bit is referred as the a founder point and it is characterized by the optimum value of WOB. A variation of the MSE value indicates that the system exits from the linear region and is foundering; in this way the real time monitoring of MSE allows the driller to verify if the system is above or below the founder point and how it reacts to the variation of defined parameters and to improve well control practices, bit selection, design of bottom hole assembly, directional target sizing and makeup torque.

It was demonstrated that the real time monitoring of MSE can reveal drilling inefficiencies and give indications on the time to pull worn Polycrystalline Diamond Compact (PDC) bits (Waughman et al., 2002); MSE and bit-specific coefficient of sliding friction were used to quantify the most common drilling issues (Pessier et al., 2012). A tool that

incorporates specific energy evaluation to model bit performance and predicts the rate of penetration of different bit types was developed (Guerrero and Kull, 2007).

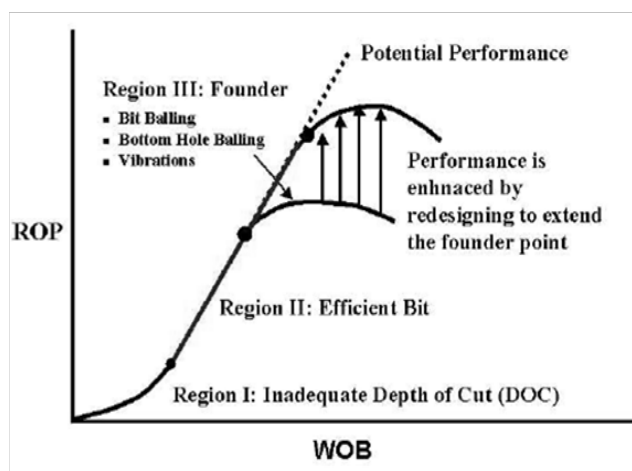


FIG. 1 DRILLOFF CURVE (DUPRIEST AND KOEDERITZ, 2005)

Experimental results demonstrated the importance of including bit hydraulics into the specific energy analysis for drilling optimization (Armenta, 2008). An attempt to better model downhole drilling was made by introducing the hydraulic energy term in the MSE correlation by means of defining it as Hydro Mechanical Specific Energy (HMSE); while experimental and field data showed that HMSE can identify inefficient drilling conditions (Mohan and Adil, 2009). The effects of changing the drilling parameters, bit wear and bit designs on ROP for both MSE and ROP model approaches were demonstrated and a commercial drilling simulator was used to model the rate of penetration sensitivities; these results were then compared to the results obtained using the MSE equation (including the bit hydraulic effects). They addressed benefits and disadvantages of using each method including their limitations and possible applications in different drilling scenarios, particularly in terms of bit runs, well simulations in real time, preplanning and post analysis (Rashidi et al., 2010). The concept of specific energy was used to develop an algorithm to estimate the technical limit of specific energy from wireline sonic, lithology and pressure data in order to represent the inherent drilling difficulty posed by the combination of rock properties, depths and pressures that make up a field's drilling environment, thereby facilitating comparisons of drilling performance from different fields that take account of varying rock drillability (Curry et al., 2005).

As demonstrated from previous studies, MSE is both a qualitative and quantitative measure that helps identify inefficiencies in the drilling process; moreover its measurement allows predicting power requirement (bit torque and rpm) for a particular bit type to drill a given ROP in a given rock type, and the ROP that a particular bit might be expected to achieve in a given rock type (Caicedo et al., 2005). In the same research work a bit-specific coefficient of sliding friction to express torque as a function of WOB and to compute specific input energy MSE in absence of down hole data has been introduced. A new method was developed to determine input variables for bit performances prediction based on the specific energy prediction and confined compressive strength; which have been integrated to provide new capabilities for rapid and accurate log-based determination of the expected achievable rate of penetration and operating parameters for all the bit types.

A new drilling rate equation that describes the effects of weight on bit, rotary speed and differential pressure on rate of penetration was introduced and the concept of founder points was revised developing a field procedure to determine how to measure the founder point at the rig. Application of this technique resulted in the maximum drilling rate possible with minimum bit wear (Robinson et al., 2001)

The monitoring of the drilling activity through the acquisition of significant parameter (to anticipate and avoid occurrence of possible problems during well drilling) has been addressed as one of the main element in the architecture of the intelligent system that they elaborated for planning an efficient oil well drilling process (Morooka et al., 2001)

#### *Evaluation of the Drilling Process Efficiency: Materials and Methods*

The MSE surveillance process provides the ability to detect changes in the efficiency of the drilling system, more or less continuously (Dupriest and Koederitz, 2005). This has improved performance by allowing the optimum operating parameters to be identified easily, and providing the quantitative data needed to cost-justify design changes to extend the current limits of the system. MSE analysis has resulted in redesign in areas as diverse as well control practices, bit selection, Bottom-Hole Assembly (BHA) design, makeup torque, directional target sizing and motor differential ratings.

The formula introduced by Teale for calculating MSE assumes that in conditions of perfect efficiency, its value would equal rock compressive strength. However, the efficiency of bits at peak performance is in the order of 30-40%, in order to make MSE easy to use tool for driller Teale proposed a value adjusted to include a mechanical efficiency factor (Effm).

In this work the modified Dupriest's formula was used as expressed in equation 1.

$$MSE_{adj} = Eff_m \left( \frac{4WOB}{\pi D^2} + \frac{480 * N * T}{D^2 * ROP} \right) \quad (1)$$

The relative variables are defined in table 1.

TABLE 1 VARIABLES OF MSE FORMULA

Variable	Definition	Measurement unit (US)	Measurement unit (SI)
MSE	Mechanical specific energy	kpsi	ksi
WOB	Weight on bit	klbs	kdaN
D	Bit diameter	Inches	mm
N	Rotary speed	RPM	RPM
T	Rotary torque	Kft.lbs	kN.m
ROP	Rate of penetration	ft/hr	m/hr

To calculated parameters of interest data acquired from down hole have been used; and the largest source of error in the evaluation of the MSE is indeed represented by the fact that surface data contain torque created by friction between the pipe and the borehole, causing drill string friction and distorting the curve in a way that the bit appears to be consuming much more energy than that in reality.

In this work data have been gathered from an innovative and versatile data acquisition and diagnostic tool consisting in a downhole multiple-sensor that allowed the real time monitoring of the drilling process as well as downhole conditions and post-well analysis with a high level of accuracy.

As an example, the difference between the surface torque (S-Torque) and the down hole one (DH-Torque), measured by the sensors placed in the drilling tool is shown in figure 2. The torque generated by the bit depends on the applied WOB, the type of formation, the bit and the mud used, the friction losses and dynamical effects; while the comparison between the S-Torque and the DH-Torque allows evaluating

the losses due to the friction amidst the tool and the hole walls.

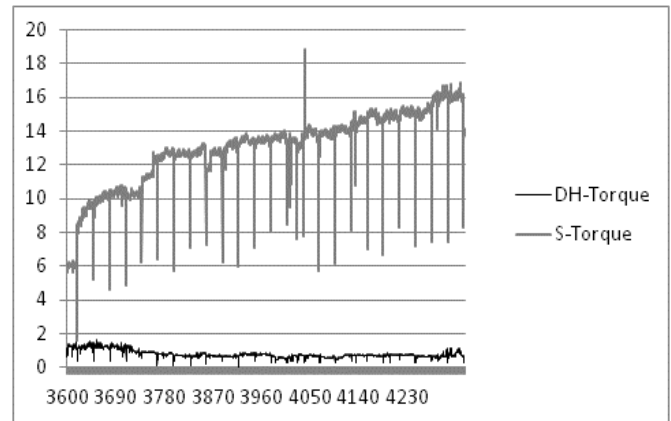


FIG. 2 DH-TORQUE VS S-TORQUE MEASURED IN WELL 1 DURING RUN 1

### 1) Measurement Tool

Beside WOB, ROP, Torque and relative MSE, there are other parameters of interest to evaluate, which can be measured by the tool containing different transducers:

- four extensimeter for the evaluation of bending moment, weight on bit and torque;
- two pressure transducers to measure internal and external pressure of the tool;
- four three-axial accelerometers for vibrations measurements;
- two magnetometers for evaluation of the rotational velocity;
- two thermocouples to measure downhole temperature.

Data are acquired and transmitted through a channel for each sensor with a frequency of 1 kHz.

The Bending Moment, generated by the gravity force acting on the drilling tool, by its contact with the hole walls, and by the curvature of the hole; is used to evaluate the curvature of the real trajectory and to compare it with the planned one. The internal and external pressure are influenced by the depth and geometry of the hole, the tool design, the loss of pressure at the bit, the flow rate and weight of the mud and ROP.

Moreover the tool is also able to monitor in real time the vibrations which allows increasing ROP, the components life and the hole quality.

All the vibrations involved in the drilling process are represented in figure 3.

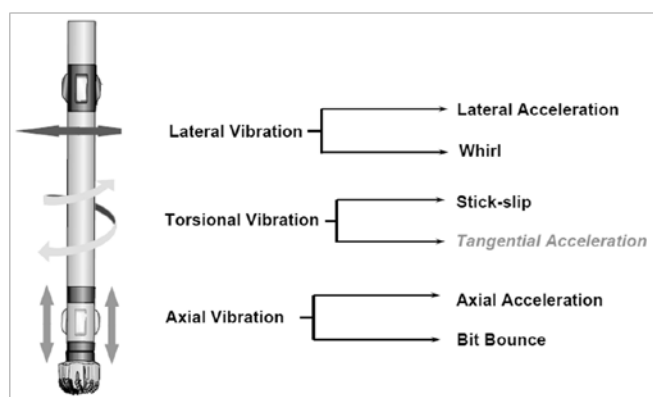


FIG. 3 TYPE OF VIBRATIONS IN THE DRILLING PROCESS

The lateral acceleration, induced by a movement perpendicular to the hole trajectory, if detected, requires immediate intervention to avoid damages to the equipments. The whirl consists in a eccentric rotation of the tool: in the forward whirl the tool rotates clockwise and causes the area of the collar that comes in contact with the hole to wear; in the backward whirl the center of the collar rotates around the center of the hole at an higher speed than expected, inducing the increase of the bending cycles and the consequent fatigue failure.

The major consequence of the whirl is a reduction of the efficiency and a larger hole diameter.

The stick-slip is a torsional vibration associated with a high torque and a fluctuation of RPM caused by the surface rotation of the drill string associated with its downhole deceleration due to the friction of the equipment with the hole walls. Also in this case it is requested an immediate intervention to avoid the ROP reduction and bit damages. Axial vibrations consist in the movement of the drill string along the hole axe; among which the most dangerous is the bit bounce.

For some of this parameters such as WOB, ROP, RPM and Torque the system visualizes the measured and processed values; for others, such as whirl and stick-slip, it provides a severity level (usually in a range from 0 to 7). Data are acquired against depth and time.

The main benefits introduced by this system are:

- real time monitoring and feedback of drilling process;
- early detection and resolution of drilling problems;
- optimization of the drilling process and relative safety issues;

- post drilling analysis and evaluation of bit performances.

### Case Study: Monitoring of Drilling Parameters

In order to analyze the drilling parameters and optimize the process, the data have been acquired from two run performed in two different horizontal wells that pass through a limestone formation. Those wells have been chosen due to the homogeneity of the formation on almost all the length of the run.

All the data have been analyzed with the help of drilling engineers working for the company producing the measurement tools.

In the following Table, the main characteristics of the wells for each run are presented.

TABLE 2 WELLS CHARACTERISTICS

	WELL 1 Run 1	WELL 1 Run 2	WELL 2 Run 1	WELL 2 Run 2
Hole diameter (in)	6"	6"	6"	6"
In depth (m)	3571	4307	4865	5392
Out depth (m)	4307	4941	5392	5952
Drilling length (m)	736	634	527	560
Drilling time (h)	159.17	130	104.25	170
Bit type	PDC bit 9 blades, 8 mm cutters	PDC bit 9 blades, 9 mm cutters	PDC bit 9 blades, 8 mm cutters	PDC bit 7 blades, 11 mm cutters

#### 1) Well 1, Run 1

In order to demonstrate the relationship between the drilling rate and performances and MSE, the following graphs present some of the main results obtained during the study.

In Figure 4, the graphs of MSEadj, ROP, WOB, RPM and Torque obtained during the first run in well 1 are presented.

In the graph of MSEadj a base-line has been drawn that separates the efficiency drilling zone from the foundering one. As an example one of this zone has been outlined, at about 4000 m of depth, which corresponds to a decreasing of ROP and an increasing of WOB and torque.

At the same depth the data show a decreasing of the tool inclination detected by the Near Bit Inclinator (NBI), a variation of the bending

moment, the zeroing of the whirl and a spike of the pressure are shown in figure 5 a) and b).

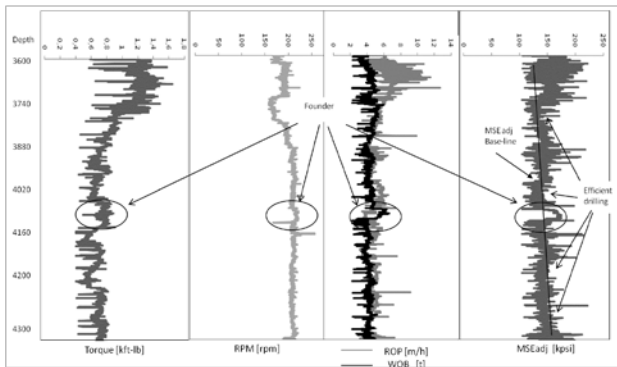


FIG. 5 A) FOUNDER POINTS IN WELL 1- RUN 1

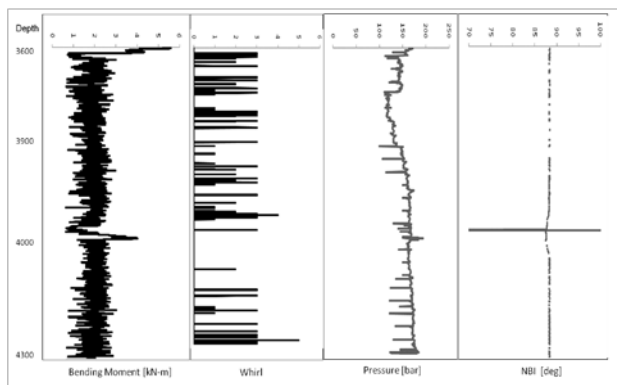


FIG. 5 B) FORMATION DEPENDENT PARAMETERS OF WELL 1- RUN 1

## 2) Well 1, Run 2

In order to assess the relationship between drilling rate and MSEadj values, a test was conducted during run 2 in well 1: WOB has been increased while observing the change of MSEadj. Results showed that if MSEadj remains close to its lowest value while increasing WOB, ROP increases linearly and the bit is operated in conditions of efficiency. Figure 6 shows the MSEadj and ROP values obtained during the test.

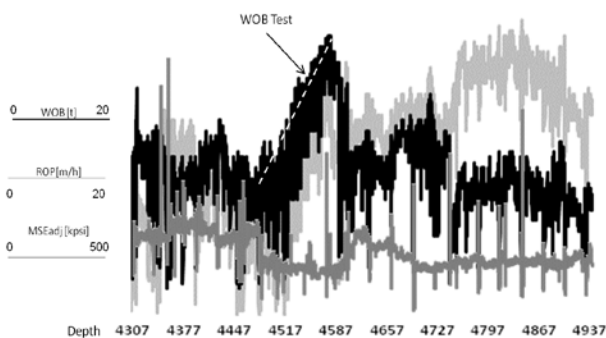


FIG. 6 WOB TEST CARRIED OUT IN WELL DURING RUN 2

Down hole data from run 2 of well 1, were implemented in the Bourgoyne and Young (1974),

model to calculate ROP that is expressed as a function of several variables such as sediments compaction, pore pressure, bit weigh, rotary speed, impact force, bit hydraulics, bit wear.

The relative equation is composed of eight terms:

$$ROP = f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8$$

Coefficients from  $a_1$  to  $a_8$  are experimental model constant and the other terms are described in table 3.

TABLE 3 TERMS OF ROP MODEL

$f_1$	$e^{2.303a_1}$	Rock drillability effect (proportional with the rock strength of the formation)
$f_2$	$e^{2.303a_2(10^3-D)}$	Depth effect (D = depth in feet)
$f_3$	$e^{2.303a_3D^{0.69}(g_p-9)}$	Pore pressure effect; g = pore pressure in pounds per gallon equivalent
$f_4$	$e^{2.303a_4D(g_p-P_c)}$	Overbalance on ROP effect; $P_c$ = mudweight in pounds per gallon
$f_5$	$\left(\frac{w}{d_b} - \left(\frac{w}{d_b}\right)^2\right)^{a_5}$	Weight on bit effect; w = weight on bit, $d_b$ = bit diameter
$f_6$	$\left(\frac{N}{60}\right)^{a_6}$	Rotary speed effect; N = revolution per minute
$f_7$	$e^{-a_7 \cdot h}$	Bit wear effect; h = amount of bit wear
$f_8$	$\left(\frac{F_j}{1000}\right)^{a_8}$	Jet impact force effect; $F_j$ = effect of bit hydraulic on ROP

The wear coefficient h was assumed equal to  $5 \times 10^{-8}$ , data to calculate the ROP as function of RPM and WOB were measured on field and the model constants provided by the company.

In figure 7 the obtained ROP map in function of different combinations of RPM and WOB values applied to the PDC bit is presented. From the map it is evident that the highest ROP value is achieved in correspondence with high WOB values with low RPM. The lowest ROP value in the lower corner of the left-hand side indicates an inadequate depth of cut due to insufficient WOB and the lowest ROP value in the right-hand side of the map, identifies the combination of WOB and RPM that determine a incomplete depth of cut due to the fact that the bit has wear out completely.

## 3) Well 2, Run 1

During run 1 of well 2 at a depth of about 5200 meters, the rock strength increased approximately of 60% (passing from around 4 ksi to 7 ksi), with a consequent drop of the drilling rate. To address the ROP decrement, WOB was increased. The

monitoring of the MSEadj value, showed a quick increment from about 50 psi to 100 psi; which exceeded by far the influence of the change in rock strength, outlining the start of a vibrational founder due to a probable damage of the bit caused by the too high WOB value. This hypothesis was verified by rig personnel after pulling out the bit. In run 2 of well 2, at a depth of about 5900 meters, the hole passed through another formation with a similar same rock strength pattern (increasing of about 50%); and rig crews were instructed to reduce the WOB in order not to damage the bit. The monitoring of MSE trend indicated when the tool had fully penetrated the stringer, the drilling parameters could be set back at their original values.

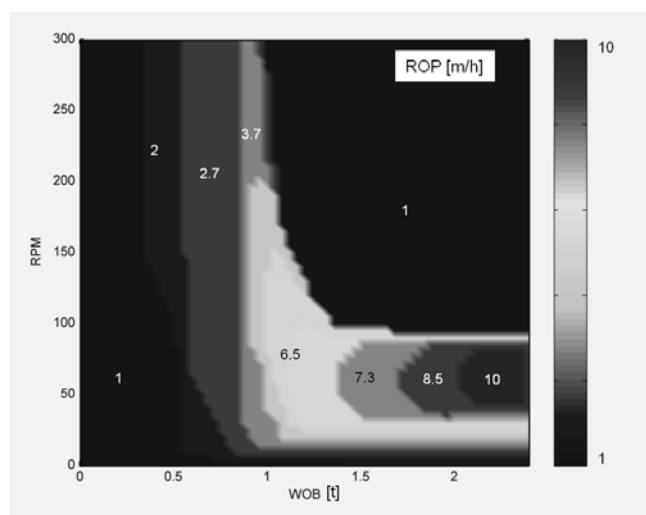


FIG. 7 ROP MAP

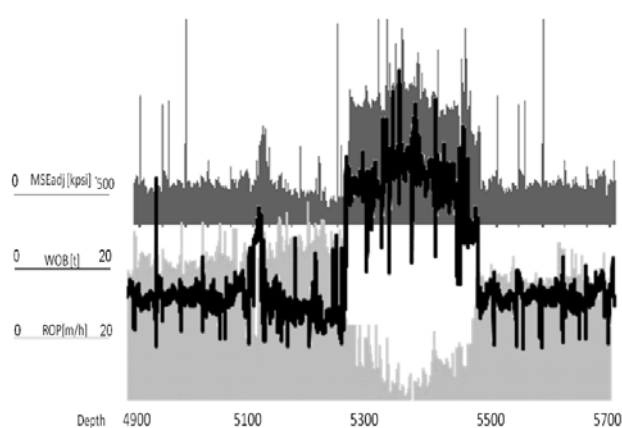


FIG. 8 VIBRATIONAL FOUNDER DUE TO BIT DAMAGE

## Conclusions

In this work data from oil field well have been used to assess the main parameters affecting the drilling process. The results obtained showed how it is

possible to use MSEadj having a monitoring tool to evaluate drilling efficiency.

In particular it has been demonstrated that increasing of MSE above an established baseline indicates that the system is foundering with consequent effects on the relative rate of penetration and other significant parameters.

From the data analysis of well 1, run 1, it is outlined that the average value for MSE is around 150 kpsi for the two run, considering a constant value for UCS of about 15 kpsi, the drilling efficiency is on the order of 10%. This result indicated that the small difference of the bits characteristics did not induce significant variations in the performances. In all the four analyzed cases it is possible to notice a massive presence of stick-slip and whirl due to the bit type and the horizontality of the hole.

Data related to the 4000 meters depth show a behavior due to a change in the lithology of the formation: the increase of the hardness induced the tool deviation and the increasing of the bending moment.

The WOB test performed in run 1 of Well 2 confirmed that when the drilling tool was operated in the linear region, e.g. in conditions of efficiency, MSE value remains constant value and close to its baseline.

The graph (at a depth from about 4730 to 4900 meters) shows also that the highest ROP value is not in correspondence with the highest WOB, suggesting that other parameters influence the system behavior which has been demonstrated by implementing the down hole well data to calculate ROP with the Borgounye & Young, (1974) model and by the relative ROP map showing the correlation between ROP, WOB and RPM.

In run 1 of well 2 it was possible to correlate the sudden increase of MSE and the severe decrease of ROP with the bit damage due to a too high WOB in correspondence of a formation with a higher rock strength. Hypothesis that was verified when in correspondence of another increase in rock strength (at a depth of about 5900 meters), the WOB was reduced instead of increased allowing the tool to fully penetrate the formation without damaging the bit.

Future researches will be related to the assessment of the measurement uncertainty, related either to the calculation of the model experimental coefficients or to the data acquired by the sensors. Sources of errors in the calculation of the significant parameters will be

identified and quantified. Moreover the research trend is to use the down hole data for feeding an intelligent systems for the management of well production.

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